Designation: E 1021 – 95

An American National Standard

Standard Test Methods for Measuring Spectral Response of Photovoltaic Cells[1]

This standard is issued under the fixed designation E 1021; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 These test methods cover the determination of either the absolute or relative spectral response of a single, linear photovoltaic cell. These test methods require the use of a bias light.

1.2 These test methods are not intended for use with interconnected photovoltaic devices.

1.3 There is no similar or equivalent ISO standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method[2]

E 772 Terminology Relating to Solar Energy Conversion[3]

E 892 Tables for Terrestrial Solar Spectral Irradiance at Air Mass 1.5 for a 37° Tilted Surface[2]

E 927 Specification for Solar Simulation for Terrestrial Photovoltaic Testing[3]

E 973 Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell[3]

E 1328 Terminology Relating to Photovoltaic Solar Energy Conversion[3]

3. Terminology

3.1 *Definitions*—Definitions of terms used in these test methods may be found in Terminology E 772 and in Terminology E 1328.

3.2 *Symbols:*

3.2.1 The following symbols and units are used in these test methods.

a—illuminated cell area, m^2,

A—irradiance normalization constant,

c—speed of light in vacuum, ms^{-1},

E—monochromatic source irradiance, Wm^{-2},

E_o— reference spectral irradiance, Wm^{-2},

h—Planck's constant, JHz^{-1},

I—current, A,

I_{sc}—solar cell short-circuit current, A,

K—relative-to-absolute spectral response conversion constant,

M—spectral mismatch parameter,

q—elementary charge, C,

Q—external quantum efficiency,

R_a—absolute spectral response, AW^{-1},

R_r—relative spectral response, and

λ—wavelength, nm or µm.

3.2.2 Symbolic quantities that are functions of wavelength appear as $X(\lambda)$.

4. Summary of Test Methods

4.1 The spectral response of the photovoltaic cell is determined by the following procedure:

4.1.1 A monochromatic, chopped beam of light is directed at normal incidence onto the cell. Simultaneously, a continuous white light beam (bias light) is used to illuminate the entire device at an irradiance approximately equal to normal end use operating conditions intended for the cell.

4.1.2 The spectral dependence of the ac (chopped) component of the short-circuit current is monitored as the wavelength of the incident light is varied over the response band of the cell. The total energy in the beam of chopped light as a function of wavelength is determined with an appropriate detector.

4.2 The absolute spectral response of a cell requires the knowledge of the absolute energy in the chopped beam. The detector must, therefore, be traceable to a National Institute of Standards and Technology (NIST) Detector Response Package,[4] or other standards for blackbody detectors as appropriate. The absolute spectral response of the cell can then be computed using the measured cell response and the irradiance of the chopped source.

5. Significance and Use

5.1 The spectral response of a photovoltaic cell is required to interpret laboratory measurements on devices and is useful for theoretical calculations. The reference cell method of

[1] These test methods are under the jurisdiction of ASTM Committee E-44 on Solar, Geothermal, and Other Alternative Energy Sources and are the direct responsibility of Subcommittee E44.09 on Photovoltaic Electric Power Conversion.

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[2] *Annual Book of ASTM Standards*, Vol 14.02.

[3] *Annual Book of ASTM Standards*, Vol 12.02.

[4] Zalewski, E. F., et al., ''The NBS Detector Response Transfer and Intercomparison Package: Its Characteristics and Use," National Bureau of Standards, Radiometric Physics Division, Washington, D.C., 1980.

photovoltaic device performance measurement, for example, requires spectral response measurements for computing the spectral mismatch parameter (see Test Method E 973).

5.2 The methods described herein are appropriate for use in either research and development applications or in product quality control by manufacturers.

6. Apparatus

6.1 *Spectral Detector*:

6.1.1 The following detectors are acceptable for use in the calibration of the monochromatic light source:

6.1.1.1 Pyroelectric radiometer, and

6.1.1.2 Calibrated photodetector.

6.2 *Monochromatic Light Source*:

6.2.1 A variety of different laboratory apparatus are available for the generation of a monochromatic beam of light. Prism or grating monochromators using tungsten or other light sources are most commonly used. Discrete and tunable continuous-wave lasers offer another source of monochromatic light. The wide range of wavelengths available coupled with the high optical quality of laser beams renders them attractive. Another source is narrow-bandpass optical filters in conjunction with a broad spectrum light source such as tungsten.

6.2.2 The monochromatic light source shall be capable of providing wavelengths that extend beyond the response region of the device to be tested.

6.2.3 A minimum of 12 wavelengths within the spectral response range of the cell to be measured is required.

6.2.4 Spectral bandwidth of the monochromatic light source shall not exceed 50 nm for a relative spectral response measurement and 20 nm for an absolute spectral response measurement.

6.2.5 The light source shall be capable of providing a spatial uniformity of ±2.5 % over the area of the test plane, and a temporal stability of ±1 % during the measurement period.

6.2.6 Care must be taken to ensure that scattered light or higher order light effects are negligible. The chopper (see 6.5) entrance and exit optics should be enclosed in a black cavity to minimize the modulation of stray light by the chopper blades.

6.2.7 It is recommended that the monochromatic light source be able to illuminate the entire area of the cell to be tested. If not, multiple measurements of the spectral response in different areas of the cell are required (see 8.2.5.1).

6.2.8 If a pyroelectric detector is used (see 6.1.1), the monochromatic source must illuminate the entire detector. If a calibrated photodetector is used, it is not necessary to illuminate the entire detector if detector response uniformity and linearity has been proven.

6.2.9 An optical shutter may be used to interrupt the monochromatic beam and, therefore, eliminate time delays involved with source and supply warm-up times.

6.3 *Monochromatic Light Chopper*:

6.3.1 A rotating mechanical light chopper or other device used to modulate the monochromatic light source.

6.3.2 The chopper blades should be non-reflective or black to minimize modulation of stray light.

6.4 *Bias Light Source*:

6.4.1 In order to measure the spectral response under conditions approximating those obtained under standard operating conditions, a bias light shall be used. The light should be of sufficient intensity to ensure the cell to be tested is operating in its linear response region, preferably within 30 % of its normal operating short-circuit current, when both the bias light and the monochromatic source are on.

6.4.2 The spectral distribution of the bias light should meet the criteria for a Class C simulator as given in Table 2 of Specification E 927. Generally, a spatial uniformity of ±10 % is adequate.

6.4.3 The bias source should contain no significant harmonics of the chopper frequency used with the monochromatic source. This can be done most easily by using a well regulated, dc power supply for the bias light. Care should be taken to prevent reflections of the bias light from the chopper blade from striking the sample. Mechanical vibrations, either from the chopper or other sources, shall not be allowed to modulate the bias light.

6.5 *Synchronous Detection Instrumentation*:

6.5.1 A pre-amplifier followed by a lock-in amplifier, ac voltmeter, or true-root-mean-square (RMS) voltmeter is used to detect the low-level, chopped signals from the photovoltaic device and thus measure the cell short-circuit current. Choice of pre-amplifier shall include consideration of the requirement that the photovoltaic cell must be operated in the short-circuit current mode and that both a low-level ac, as well as a high-level dc signal will be present. Under these conditions a pre-amplifier with a transformer coupled input circuit may saturate and result in inaccurate readings. If the pre-amplifier is not a low input-impedance, short-circuit current type and the photovoltaic device is loaded in the short-circuit mode with a four-terminal resistor instead, one must ensure that the drop across the load resistor is less than 20 mV. The dynamic range required of the instrument will depend on the chopped beam source used. For example, a tungsten source with a monochromator will usually require a dynamic range of four to six orders of magnitude, because of the wide range of intensity variation over the required spectral test range.

6.5.2 For relative spectral response measurements, it is not necessary for the synchronous detection instrumentation to output the short-circuit current in amperes. A lock-in amplifier, for example, might give the short-circuit current in microvolts which does not then need to be converted to the actual current in amperes.

6.5.3 True-RMS voltmeters respond to both the ac and the dc components of the short-circuit current which then must be separated to determine the ac component. An acceptable method uses the square root of the difference of the square of the signal and the background (or noise) signal.

6.6 *Test Plane*:

6.6.1 The test plane shall consist of means to mount the photovoltaic cell to be tested in a position to allow illumination by both the monochromatic and bias light sources.

6.6.2 The test plane also shall allow the spectral detector (see 6.4) to be illuminated by both the monochromatic and the bias light sources in the same plane as the photovoltaic cell.

6.6.3 The test plane shall allow for temperature regulation of the cell to 25 ± 5°C.

7. Hazards

7.1 **Precaution**—In addition to other precautions, eye safety wear must be worn to protect against possible damage from the particular light sources used, particularly if a laser is employed as the monochromatic light source. High voltages may also be present when lasers or arc lamps are used. Usage of arc lamps also presents a high ultraviolet component, as well as the possibility of bulb explosion. Light choppers can present a mechanical hazard when rotating at high speeds.

8. Procedures

8.1 Two measurement procedures are given: the first a sequential method using one test plane; the second uses a one-pass technique. Either of the two methods may be used. Fig. 1 indicates how both methods may be used with a monochromator or a set of narrow-bandpass filters, and a lock-in amplifier. For both methods, the following restrictions apply:

8.1.1 Spectral response must be measured at a minimum of 12 wavelengths throughout the spectral response range of the cell to be tested.

8.1.2 For absolute spectral response measurements, the total monochromatic irradiance on the test plane is determined as a function of wavelength along with the short-circuit current (in amperes) of the cell to be tested.

8.1.3 Relative spectral response measurements require only the relative intensity versus wavelength to be determined with the detector.

8.1.4 If the detector does not have a flat spectral response over the measurement wavelengths, a correction for the spectral response of the detector will be required to compensate for the detector's non-flat response.

8.2 *Method A*:

8.2.1 Mount the spectral detector in the test plane and illuminate the entire area of the detector with the dc bias light.

8.2.2 Measure the noise level at the output of the detector while the monochromatic light source is turned off. The noise level must be less than 1 % of the smallest signal value observed for the incident power within the wavelength interval as measured in 8.2.4.

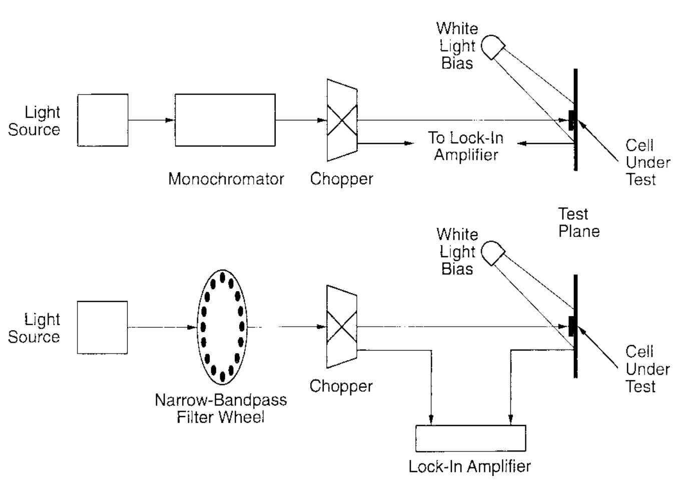

FIG. 1 Monochrometer or Narrow Bandpass Filters Measurement Schematic

8.2.3 Turn on the monochromatic light source.

8.2.4 Measure the source irradiance as a function of wavelength, using the detector output and meeting the requirement of 8.1.1. The wavelengths used for the source irradiance and the spectral response measurements (see 8.2.8) must be identical.

NOTE 1—For pyroelectric detectors, it may not be appropriate for the bias light to be on during the irradiance measurements.

8.2.5 Turn off the monochromatic beam and replace the detector with the cell to be tested.

8.2.5.1 The cell should be mounted in the test plane such that the chopped beam is intercepted predominantly by the active surface area of the cell. The preferred method is to illuminate the entire cell, thereby averaging out the spatial and spectral variations over the surface area. If the chopped beam does not cover more than 25 % of the cell area, then at least four sets of measurements, one near the center of the cell's four quadrants, must be obtained.

8.2.6 Scan the entire wavelength range and measure the noise level of the system as a function of wavelength by recording the output of the synchronous detection instrumentation.

8.2.6.1 The noise level must be less than 10 % of the smallest value observed for the spectral response within the measurement wavelength interval.

8.2.7 Turn on the monochromatic light source.

8.2.8 At each wavelength selected for the spectral response measurement (see 8.1.1), record the output of the synchronous detection instrumentation.

8.3 *Method B*:

8.3.1 Mount the cell to be tested and the detector in the test plane and direct the chopped, monochromatic light source onto both, following the provision of 8.2.5.1. This may be accomplished either through diversion of the beam to two separate equivalent test planes, or by locating the cell and the detector in a single test plane. If two separate test planes are used, the intensity of the light source on each of the two planes shall be known to within ±2 %.

8.3.2 Verify that the conditions of 8.2.8 are met.

8.3.3 Turn off the monochromatic light source and turn on the bias light source.

8.3.4 Measure the noise level of the detector as in 8.2.2.

8.3.5 Measure the noise level of the system as in 8.2.6.

8.3.6 Turn on the monochromatic light source.

8.3.7 Set the monochromatic light source to the desired wavelength, and record the detector output.

8.3.8 Record the output of the synchronous detection instrumentation at the same wavelength as used in 8.3.6.

8.3.9 Repeat 8.3.6 and 8.3.7 to meet the requirements of 8.1.1.

9. Calculation of Results

9.1 *Relative Spectral Response*—The relative spectral response (see 8.1.3) is calculated in accordance with 9.1.1 if the monochromatic light source illuminates greater than 25 % of the cell area, and in accordance with 9.1.2 if illumination covers less than 25 % of the cell area.

9.1.1 *Illumination > 25 % of Cell Area*:

9.1.1.1 A correction factor, *A*, which normalizes the monochromatic light source to constant irradiance across the spectral range of the measurement, is calculated at each of the measurement wavelengths. These factors, A_I through A_N, where *N* is the number of measurement wavelengths, are determined by dividing the maximum spectral detector output by the spectral detector output at each wavelength. The correction factors correspond to the intensity variations of the monochromatic light source at each of the measurement wavelengths.

NOTE 2—The spectral detector output, as previously discussed in 8.1.4, must also have been normalized if the detector does not have a flat response curve over the measurement wavelengths.

9.1.1.2 Multiply each of the synchronous detector readings, *I*, by the corresponding correction factor *A*. Therefore, the relative spectral response at the third measurement wavelength is:

$$R_{r3} = I_3 \times A_3 \tag{1}$$

9.1.2 *Illumination <25 % of Cell Area*:

9.1.2.1 Calculate the correction factors, *A*, in accordance with 9.1.1.1.

9.1.2.2 For each quadrant of the cell (see 8.2.5.1), determine the relative spectral response in accordance with 9.1.1.2.

9.1.2.3 Average the four relative spectral response measurements at each wavelength to obtain the final spectral response.

9.1.3 Normalize the relative spectral response by dividing each value by the maximum spectral response. The relative spectral response will then be a maximum at unity.

9.1.4 The relative spectral response is then plotted versus wavelength and also tabulated as X-Y data pairs.

9.1.5 Relative spectral response can be converted to absolute spectral response with a multiplicative constant.

9.1.5.1 The conversion constant can be obtained, for example, from an accurate measurement of the absolute spectral response at a single wavelength λ_o (such as might be obtained with a laser) by:

$$K = R_r(\lambda_o)/R_a(\lambda_o) \tag{2}$$

9.1.5.2 Alternatively, *K* can be calculated using the short-circuit current of the photovoltaic cell when illuminated by a known spectral irradiance. The most convenient spectral irradiance for this calculation is one of the reference spectral irradiance distributions in Tables of E 892. *K* is calculated as follows:

$$K = \frac{I_{sc}}{aM} \div \int R_r(\lambda)E_o(\lambda)/d\lambda \tag{3}$$

9.2 *Absolute Spectral Response*:

9.2.1 Calculate absolute spectral response at each measurement wavelength using:

$$R_a = \frac{I}{aE} \tag{4}$$

NOTE 3—Because absolute spectral response is dependent upon the actual cell area illuminated, any grid lines or contacts blocking the monochromatic light must be accounted for by subtraction from the illuminated cell area. Also, any error in the area measurements will be transferred directly to the absolute spectral response, and therefore should be minimized.

9.2.2 The absolute spectral response is then plotted versus wavelength and also tabulated as X-Y data pairs.

9.2.3 Absolute spectral response may also be converted to external quantum efficiency, with the dimensionless units of electrons per photons, using:

$$Q = \frac{hc}{q}\frac{R_a}{\lambda} \times 10^6 = 1.239852\frac{R_a}{\lambda} \tag{5}$$

for wavelength units in µm.

10. Precision and Bias

10.1 *Interlaboratory Test Program*—An interlaboratory study of spectral response measurements was conducted in 1992 through 1994. Seven laboratories performed three repetitions on each of ten solar cells circulated among the participants. The design of the experiment, similar to that of Practice E 691, and a within-between analysis of the data are given in ASTM Research Report No. RR: E44 – 1003.

10.2 *Test Result*— Analysis of data from interlaboratory studies of spectral response measurements is complicated by the lack of a single numerical result (see 9.2.2). This complication was overcome by performing a reference spectral mismatch parameter calculation in accordance with Test Method E 973 using the spectral response data submitted by the participants. Because of the normalization inherent in spectral mismatch calculations, the precision information given below in percentage points is representative of relative spectral response measurements.

10.3 *Precision*:

95 % repeatability limit (within laboratory)	0.3 %
95 % reproducibility limit (between laboratory)	1.7 %

10.4 *Bias*—The contribution of bias to the total error will depend upon the bias of each individual parameter used for the determination of the spectral response. The procedures prescribed in these test methods are designed to reduce bias errors as much as is reasonably possible.

10.4.1 For relative spectral response measurements, wavelength-independent bias errors cancel because of the normalization performed. However, bias errors that vary with wavelength (such as errors due to nonflat detector response) will still introduce error into the final results.

10.4.2 For absolute spectral response measurements, bias errors do not cancel out from normalization and therefore propagate directly into the final results. Of all possible sources of bias, two will most likely dominate the total error: detector calibration and the area measurements.

11. Keywords

11.1 cell; measurement; photovoltaic; response; spectral; testing